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THE NATION'S LABORATORY FOR ADVANCED AUTOMOTIVE TECHNOLOGY

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Field Demonstration of Biobased Hydraulic Fluids in Military Construction Equipment

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By

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13. ABSTRACT (Maximum 200 words) TARDEC has initiated a joint field demonstration program with US Department of Agricultural (USDA)and PM of Combat Engineer/ Materiel Handling Equipment to evaluate biobased hydraulic fluids in military construction hydraulic systems. The objective of this program is to introduce the environmentally acceptable hydraulic fluids into military hydraulic systems. Five biobased fluids qualified under MIL-PRF-32073 specification were tested in ten pieces of military construction equipment at Fort Leonard Wood, MO for a year. The test results showed that biobased fluids tested did not show any abnormal behavior in this demonstration and provided acceptable performance comparable to the existing petroleum based fluids. In addition, no equipment failed or was damaged due to the biobased fluids. Therefore, the biobased fluids can be used as an operational fluid for the hydraulic systems of military construction equipments.				
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EXECUTIVE SUMMARY

U.S. Army Tank-Automotive RD&E Center is currently developing biobased hydraulic fluids (BHF's) to replace military industrial and mobility hydraulic fluids that are incompatible with the environment and to meet DOD Hazardous Waste Minimization (HAZMIN) Policy. Currently, the biobased hydraulic fluids are formulated with renewable products such as rapeseed, sunflower, corn, soybean, canola and synthetic ester. These types of fluids are currently considered less toxic and more biodegradable than conventional hydraulic fluids. Initiating development of such products was most timely in view of the new Federal Biobased Products Preferred Procurement Program being developed to implement Section 9002 of the Farm Security and Rural Investment Act of 2002. This procurement program should provide for preferred procurement by all Federal agencies of qualifying biobased products. Federal agencies, however, need not purchase biobased products that do not meet the reasonable performance standards of procuring agencies. Hence, testing of biobased products to determine that they meet the performance standards of the procuring agencies is critically important to qualifying these products for preferred procurement under the Program. To accept biobased hydraulic fluids, MIL-PRF-32073 specification on Biobased Hydraulic Fluids (BHF's) has been developed for military hydraulic systems.

To verify the performances of these biobased fluids in military construction equipments, a joint field demonstration was initiated with US Department of Agricultural (USDA) and PM for Combat Engineer/ Materiel Handling Equipment using ten military construction equipment (i.e., Bulldozer, Scraper, Grader, Loader, Crane, etc.) at Fort Leonard Wood, MO. The duration of this field test was designed for one year and the acceptance of the BHF's was determined based on the field testing evaluation and resultant finding generated. The field demonstration was successfully completed, met original milestones, and did not impact the military mission of the unit in any way. The test results showed that BHF's did not provide any abnormal behavior compared to the conventional petroleum based fluids and the overall performance of these products have been proved in the construction equipments and accepted by military users. Therefore, it is recommended that the biobased hydraulic fluids qualified under the MIL-PRF-32073 specification can be used as an operational fluid for construction equipment.

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I. BACKGROUND

Environmental safety and compliance has recently become the most significant worldwide issue. Over the past decades, many military installations throughout the United States have been contaminated with petroleum and related fuels, lubricants and associated products, such as lubricating oils, greases, hydraulic fluids, aircraft and automotive fuels, and those fuels used for fixed installations¹. The environmental threats or damage to soils, surface water, and underground water were often caused by leaking containers, accidental spills, or equipment breakdown during active use or storage of these materials. The generation of the potentially hazardous wastes by Petroleum, Oil, and Lubricant products (POL) not only cause both short and long term liability with respect to environmental damage, but can result in deteriorated mission performance and high cleanup costs. Currently, the Resource Conservation and Recovery Act (RCRA)² and the DoD Hazardous Waste Minimization (HAZMIN) Policy mandate that all DoD installations must reduce the quantity or volume and toxicity of hazardous waste generated by POL wherever economically practicable and environmentally necessary. To achieve the HAZMIN goals, U.S. Army Tank-Automotive RD&E Center is currently developing the bio-based hydraulic fluids (BHF) to replace military industrial and mobile hydraulic fluids that are incompatible with the environment. Initiating development of such products was most timely in view of the Executive Order No. 13134 on Developing and Promoting Biobased Products and Bioenergy.

A biobased hydraulic fluid is currently defined as a fluid formulated with oils extracted from renewable resources such as plants, crops, trees or animals. The U.S. Department of Agriculture (USDA)'s biobased product guideline also defines exactly what products and how much concentration of renewable product associated with final product would be considered as a biobased product³. Currently, biobased hydraulic fluids are formulated with renewable products such as rapeseed, sunflower, corn, soybean, canola, and synthetic ester. These types of fluids are considered less toxic and more biodegradable than conventional hydraulic fluids⁴. The chemical structures of vegetable oils are triglycerides in which a variety of saturated, monounsaturated or polyunsaturated fatty acids are esterified to a glycol backbone. The physical properties of a vegetable oil depend on the nature of its fatty acid composition. Some synthetic esters are also made from renewable sources instead of the petroleum sources. Their biodegradability is comparable to vegetable oils and the lubrication properties are very similar to mineral oils. But, they do not have identical chemical structures and lubrication properties⁵.

In response to the demand of military BHF, a limited field demonstration was conducted at Fort Bliss, TX, in 1999 using five experimental biodegradable hydraulic fluids (i.e., rapeseed oil, soybean oil, canola oil, synthetic ester oil) and ten construction and tactical equipment (i.e. scoop loaders, dump trucks, road graders, etc.)⁶. The field test results showed that all candidate BHF samples did not give any abnormal behavior and provided excellent service. Based on the successful completion of first Phase of this field demonstration, a new military performance specification, MIL-PRF-32073, Hydraulic fluid, Biobased, was developed to cover the hydraulic fluid requirements of military construction and tactical equipment⁷.

To introduce the biobased hydraulic fluids into military construction equipment, the second Phase of the field demonstration was initiated using the five BHF's qualified under MIL-PRF-32073 specification and ten pieces of construction equipment utilized in the Engineering School at Fort Leonard Wood, MO. This program was originally designed in a joint effort with USDA and Program Manager for Combat Engineer and Materials Handling Equipment (PM CE/MHE), and supported by Federal Biobased Products Preferred Procurement Program being developed to implement Section 9002 of the Farm Security and Rural Investment Act of 2002. The duration of this field test was one year and the acceptance of the BHF's in the construction equipment was based on the field testing evaluation and resultant finding generated. The field demonstration has been completed, and this report presents the results of the study, along with recommendations and a future plan.

II. FIELD DEMONSTRATION PROGRAM

(a) Objective

The objective of this field demonstration was to verify performance of MIL-PRF-32073 Biobased Hydraulic Fluids (BHF's) for existing military construction equipment in cooperative effort with USDA, TARDEC Construction Engineer Team and Product Manager for Combat Engineer and Materials Handling Equipment (PM CE/MHE). Successful completion of this demonstration would result in the existing petroleum based hydraulic fluids used in construction equipment being replaced with non-toxic and biodegradable products.

(b) Scope

The field test at Fort Leonard Wood, MO was focused on Bio-based Hydraulic Fluids performance in military construction equipment and the potential environmental acceptability of MIL-PRF-32073 fluids. The candidate BHF products were evaluated in a wide variety of military construction equipment. The duration of this field test was designed for a one year testing period. The final acceptance of the BHF's was based on the field testing evaluation and resultant findings generated. If MIL-PRF-32073 fluids are acceptable during this testing period, the field test will be extended to two more years to determine their service life.

(c) Field Testing Sample

Five BHF's qualified under the MIL-PRF-32073 specification were selected as field testing samples. These biobased fluids have been fully evaluated under laboratory environments, and have met all specification requirements. For the field test, 18 drums of MIL-PRF-32073 fluids were procured directly from four renewable oil companies. Their physical properties and identifications are described in Table 1. The fluids were identified by their codes and color.

Table 1. Biobased Hydraulic Fluids Selected for the Field Demonstration

Code with Color	Product name	Viscosity @40 °C	Pour point ,°C	Biodegradability for 28 days, %	Spec Grade	QPL Number	Company
A (Red)	Cognis Proeco EAF 422 LL	22.6	-51	66	2	BHF-01	Cognis
B (Blue)	Novus 100 ISO 46	42.0	-44	72.7	4	BHF-02	Cargill
C (Yellow)	Hydro Safe ISO VG68M5	68.6	-37	68.3	5	BHF-07	Hydro Safe
D (Green)	Terresolve EL 146	46.6	-25	85	4	BHF-08	Terresolve
E (Orange)	Hydro Safe ISO32M3B	40.3	-35	71	3	BHF-09	Hydro safe

(d) Field Demonstration Sites and Procedure:

MIL-PRF-32073 products were evaluated using the normal procedures utilized for construction equipment. A total of 10 pieces of construction equipment were used for this field test at Fort Leonard Wood. These vehicles belong to the Engineer School and are used for training Soldiers. The environment of this location has a typical Midwest weather and is a normal operation site. The test vehicles were selected based on availability and typical military applications and are listed in Table 2. In preparation of this field demonstration, the existing petroleum based hydraulic fluids (SAE 15W-40 or MIL-PRF-2104) were completely removed from hydraulic systems of the construction equipment, and the inspection was conducted on the surface of these parts/components to determine whether the systems were leaking or not. The candidate BHF's were then introduced using the following changeover procedure;

1. Operate the equipment for 15-20 minutes to warm the system.
2. Drain the fluid from the reservoir and total systems such as pumps, lines and hoses.
3. Refill the system with the appropriate fluid selected for each system and install a new filter, and again operate the system for 15-20 minutes.
4. At the end of the second warm-up period, drain and replace the fluid with a fresh change of a test fluid mentioned in the above step 3 and install a new filter.

After the completion of changeover procedure, the equipment was operated again for a short demonstration period to ensure that the hydraulic system is operated normally. The tested construction equipment must be operated a minimum for 5 hrs per week in routine military operations. During the tests all performance should be observed, and fluid level periodically inspected. The test fluids were sampled at the each quarter and their deterioration was evaluated

in the laboratory.

Table 2. Construction Equipments Selected for Field Demonstration

Code	Name	Military Code	Serial No.	Registration No.	Bumper No.	Hour Operation	Oil tank size, gal	Test oil
F-1	Bulldozer	D7G	3ZD00136	UC03VS	B210	4410	21	A, Red
F-2	Bulldozer	D7G	3ZD00021	UC04AO	B213	3446	21	D, Green
F-3	Scraper	621B	2DB00375	UA038Z	B401	2587	30	D, Green
F-4	Scraper	621B	2DB00370	UA036Y	B400	2171	30	E, Orange
F-5	Grader	130G	7GB00343	UE01VZ	B156	904	8	E, Orange
F-6	Grader	130G	7GB00697	UE04T5	B122	4050	8	A, Red
F-7	Loader	MW24C	9160252	UE0325	B931	3340	29	E, Orange
F-8	Excavator	SEE	96HMH50156	UC03L3	B840	1030	45	B, Blue
F-9	Crane	ATEC	86613	UD02G1	B309	667	66	B, Blue
F-10	Crane	ATEC	86614	UD02G2	B310	711	66	C, Yellow

(e) Schedule:

Milestone

Completion Date

Coordinate project with USDA and Bio-based oil companies.

1Q FY05

Evaluate candidate bio-based hydraulic fluids against MIL-PRF-3207 requirements

Continue over program

Develop a field demonstration plan with PM of construction and TARDEC construction office

3Q FY05

Procure test samples for the field demonstration

3Q FY 05

Start Field demonstrations using the selected equipment

4Q FY05

Monitor the field demonstration

Collect data at each quarter

Complete the field Demonstration Laboratory Evaluation
07

4Q FY 06
2Q FY

Prepare Final Report

4Q FY07

(f) Data Collection:

All testing results and operator/user comments were recorded. TARDEC collected data including system inspections from maintenance personnel of Fort Leonard Wood and reviewed the data on a quarterly basis. The following performance characteristics were closely monitored at the testing site.

- Checked overall performance of new fluid and compared to existing conventional fluid.
- Any material incompatibility was observed (e.g., softens hoses, seals, etc).
- Low temperature operaterability was observed (e.g., fluid pumpability, freezing, etc.).
- Fluid evaporation in the system was checked (e.g., fluid level, etc.).
- Fluid condition was checked using laboratory tests (e.g., viscosity, TGA, PDSC, water content, etc.).
- Environmental assessment was determined (i.e., health and safety factors, operator Acceptability, etc).

III. FIELD TEST RESULTS

A summary of the field demonstration is presented in Table 3. The equipment and fluids tested are identified by their designated codes. Data obtained for BHF's were generated from ten construction equipment that were utilized for the military training in Engineering School located at Fort Leonard Wood. Per the test plan, the tested equipment has been quarterly inspected and the field samples (2 OZ) were collected for the laboratory evaluation⁸. During the inspection periods, the equipment usages were recorded, and their hydraulic components and fluid levels were visually inspected (i.e., leaking spot, wear and corrosion problems, fluid condition, contamination, biodegradation, etc). Total equipment usages of this demonstration ranged from 135 to 393 hours operation. The usage of the construction equipment is normally measured by an hourly base rather than mileage of vehicles. Fort Leonard Wood is located at Midwest and its annual temperature ranges from 0 to 38 °C. In this demonstration, any equipment or operational problems were not detected or notified from the 577th maintenance personnel and equipment operators. In addition, no biodegradation was observed in any equipment tested. In a visual inspection, the BHF's did not provide any abnormal behavior and have performed well in the construction equipment as the original petroleum based hydraulic fluids. Representative photographs taken from the testing sites are provided in Appendix A.

Table 3. Results of Field Demonstration for Biobased Hydraulic Fluids

Code	Name	Bumper No.	Equipment Usages (hrs)					Test oil	Leaking or other Operational problem	Fluid condition (visible inspection)
			1Q	2Q	3Q	4Q	Total			
F-1	Bulldozer	B210	75	9	112	80	276	A	No	Clean
F-2	Bulldozer	B213	38	94	55	71	258	D	No	Clean
F-3	Scraper	B401	92	81	47	92	312	D	No	Clean
F-4	Scraper	B400	64	23	92	107	286	E	No	Dark color
F-5	Grader	B156	8	23	62	103	196	E	No	Clean
F-6	Grader	B122	126	10	129	128	393	A	No	Clean
F-7	Loader	B931	79	15	39	139	272	E	No	Clean
F-8	Excavator	B840	2	3	3	42	50	B	No	Clean
F-9	Crane	B309	10	35	43	47	135	B	No	Clean
F-10	Crane	B310	24	102	31	86	243	C	No	Clean

Hydraulic fluid is an essential and important component of any hydraulic power system. This fluid is currently formulated to provide the medium for efficient power transmission and lubrication to the system. In addition, the fluid should protect the system from corrosion and excessive wear, and must be compatible with seal materials to avoid leaking problems in the system. The excessive leaking of fluid can result in the loss of hydraulic power and create environmental problems such as soil contamination. In general, the fluid must be compatible with structural materials of the system and should exhibit stable physical properties during a suitable period of use and storage. Typically, the biobased fluid must not show any sign of biodegradation in the system.

To evaluate the field samples, a test protocol was developed based on the above mentioned field performance criteria. It consists of viscosity testing, water content, oxidation stability, evaporation loss, low temperature stability, element analysis (wear), and composition analysis. Most of these tests are currently specified in the MIL-PRF-32073 specification. Table 4 describes the test protocol used in this field demonstration. For the baseline study, the existing petroleum based hydraulic fluids (SAE 15W-40 or MIL-PRF-2104) collected from the hydraulic system of each piece of tested construction equipment were also evaluated according to the test protocol. Table 5 summarizes the test results of existing fluids by their equipment's bumper numbers. The element analysis of the exiting fluids is presented in Table 7 with the biobased fluids. Table 7 -11 presents the laboratory test results of field samples collected at each quarter. The tested equipment and samples are represented by their designated codes. The QPL data of BHF's tested are also attached in Appendix B for reference purpose.

Table 4. Test Protocol for Laboratory Evaluation

Test	Method
Viscosity	ASTM D 445

Water content	ASTM D 6304
Oxidation Stability	ASTM D 6186
Total Acid Number	ASTM D 664
Evaporation	ASTM E 1131
Low temperature Stability	ASTM D 6351
Elemental Analysis	X-ray Technique
Composition Analysis	ASTM D7373
Biodegradation	ASTM D 7373, ASTM D 6731

Table 5. Test Results obtained from Existing Petroleum based Hydraulic Fluids Collected from Tested Equipment

Bumper Number	Viscosity (cSt)			Oxidation Stability @180°C, min	Evaporation @100 °C for 1 hr, %	Total Acid number Mg KOH/g	Low temperature Stability (minimum temperature, °C)
	40 °C	100 °C	VI*				
B122	55.50	8.288	122.2	21.83	1.829	1.87	-25
B309	44.41	7.104	119.7	30.99	1.029	2.24	-25
B310	44.06	7.083	120.5	23.48	1.048	2.15	-25
B213	69.91	9.904	123.6	40.22	0.6497	2.59	-25
B401	53.11	8.147	124.1	90.96	0.5353	2.11	-25
B210	81.97	10.88	119.5	24.03	0.7516	2.30	-25
B156	60.10	8.596	116.0	31.36	1.335	2.01	-25
B840	39.59	6.689	124.5	36.26	0.8058	1.97	-25
B931	35.76	6.133	118.9	58.16	0.8824	1.65	-25
B400	64.04	9.486	128.6	76.70	0.390	2.15	-25
SAE 15W-40	97.56	13.60	142.2	14.0 @210C	0.3636	2.55	-25
MIL-PRF-2104	45.8	12.8		53.37	0.9006	2.27	-25

* Viscosity Index

For the field demonstration, five BHF's were introduced into ten pieces of construction equipment. To increase the reliability of data, Fluids A, B, and D were each tested in two different pieces of equipment. Fluid E was tested in three pieces of equipment and Fluid C was

tested in one construction equipment. According to the changeover procedure, all existing petroleum based fluids (SAE 15W-40 or MIL-PRF-2194) were completely drained and the hydraulic systems were refilled two times with tested biobased fluids to minimize the contamination from the existing hydraulic fluids. Then, the samples were collected from each equipment for the laboratory composition analysis. The composition analysis of the field samples are shown in Table 6 with their biobased fluids. The results showed that all biobased fluids were contaminated with 18 to 42.1 percent petroleum based fluids. It appeared that some of existing fluids were still remaining in the system due to the difficulty of cleaning the whole hydraulic system. For example, seals and hoses can become entrained with fluid which leaches out over time. Generally, it is almost impossible to remove all existing fluids from equipment except for a new system that is not lubricated with fluid. This is one issue raised when the different types of fluids are introduced into the existing system. Table 7 lists the actual composition of the tested fluid in each equipment.

Table 6. Composition Analysis for Field Samples

Sample		Chemical Composition, %							
Code	I.D	Saturate		Non-polar Aromatics		Ester		Polar Aromatics	
		1Q	4Q	1Q	4Q	1Q	4Q	1Q	4Q
F-1	A	55.49	53.61	3.99	3.91	33.76	39.63	6.76	2.85
F-2	D	14.21	14.97	4.94	3.89	74.07	76.94	6.78	4.20
F-3	D	26.02	28.33	5.22	5.86	61.09	60.80	7.68	5.0
F-4	E	34.21	34.05	6.15	4.73	53.03	59.4	6.61	1.82
F-5	E	42.96	52.12	9.17	8.32	41.26	36.58	6.61	2.98
F-6	A	61.35	61.47	7.61	7.06	21.13	23.47	9.91	8.0
F-7	E	39.77	40.44	5.11	4.97	46.99	48.34	8.14	6.26
F-8	B	33.24	26.39	10.55	5.91	53.89	66.66	2.32	0.54
F-9	B	18.43	27.00	4.30	5.59	73.29	72.24	3.98	6.03
F-10	C	35.77	31.84	4.05	3.89	58.06	58.4	2.14	5.84
A	-	50.50	50.13	0.61	1.20	39.32	39.63	9.57	9.03
B	-	3.30	3.29	3.01	3.13	90.52	87.3	3.16	6.27
C	-	15.76	15.65	2.56	2.20	75.99	78.91	5.69	3.24
D	-	2.65	2.52	2.14	2.63	89.54	88.42	5.67	6.44
E	-	16.22	14.74	1.56	2.44	76.66	77.81	5.56	5.0
SAE 15W-40	-	86.59	-	10.69	-	1.48	-	1.32	-
MIL-PRF-2104	-	77.48	-	19.94	-	1.25	-	1.34	-

Table 7. Composition of the Tested Samples in the Equipment

Equipment Code	SAE 15W-40 or MIL-PRF-2104, %	Biobased Fluid from MIL-PRF-32073, %
F-1	19.7	80.3
F-2	16.8	83.2
F-3	34	66
F-4	18	82
F-5	30.7	69.3
F-6	40.9	59.1
F-7	23.6	76.4
F-8	42.1	57.9
F-9	18.1	81.9
F-10	28.8	71.2

Viscosity is an important property in hydraulic fluids and provides the lubrication of moving parts in a hydraulic system. This property directly affects flow characteristics, heat generation within system, pumping operation, sealing, leaking characteristics. The viscosity of fluids is often measured using the ASTM D 445, Kinetic Viscosity of Transparent and Opaque Liquids. This test method covers the determination of kinetic viscosity of fluids. The viscosity values most frequently measured for a fluid are at 40 and 100 °C at atmospheric pressure and low-shear rates. Currently, military biobased hydraulic systems use many different types of viscosity grades (ISO VG 15, 22, 32, 46, and 68) as an operational fluid. For this reason, the five different types of viscosity grades were selected for the test samples. Viscosity index (VI) is also used for measure of how viscosity changes with temperatures. Generally, a high VI indicates that the viscosity of fluids undergo less change with temperature variations. Table 8 summarizes the viscosity data of all samples collected at each vehicle inspection period. The viscosity data of biobased samples collected from original drums are also presented in Table 8. They usually change slightly with time due to the test precision and aging. It was observed that the viscosities of field samples were not significantly changed over the one year period. Also, the viscosities of biobased fluids obtained from drums were not significantly changed for a year. This result indicated that the field samples were still in good condition.

Table 8. Viscosity Test Results

Sample Code	1Q			2Q			3Q			4Q		
	40°C	100°C	VI	40°C	100°C	VI	40°C	100°C	VI	40°C	100°C	VI
F-1	25.75	5.403	151.4	25.5	5.37	151.5	25.35	5.323	149.8	26.18	5.470	152.0

F-2	45.72	9.971	212.8	57.73	11.70	203.1	57.43	11.44	198.1	57.50	11.41	197.1
F-3	42.63	8.966	198.3	42.26	8.751	192.8	42.13	8.793	195.0	42.13	8.73	192.7
F-4	42.95	8.417	177.0	43.3	8.372	173.3	42.94	8.319	173.3	44.90	8.74	177.9
F-5	45.56	8.337	160.8	37.90	7.218	157.3	37.98	7.204	156.2	41.02	7.562	154.2
F-6	32.19	6.148	142.5	31.4	6.001	140.2	83.31	11.30	126.7	31.08	5.954	140.0
F-7	38.07	7.544	170.5	32.02	6.557	165.5	31.72	6.492	164.3	31.56	6.461	163.7
F-8	38.70	7.837	179.7	39.25	7.949	180.2	41.77	8.66	192.4	41.69	8.646	192.3
F-9	42.32	8.713	191.0	42.81	8.551	182.4	41.6	8.462	186.1	41.29	8.415	186.2
F-10	57.18	10.68	180.4	58.39	10.76	177.9	59.54	10.70	172.3	56.43	10.46	177.6
A	23.64	5.184	157.9	-	-	-	-	-	-	22.39	4.872	146.3
B	42.11	9.069	204.8	-	-	-	-	-	-	43.34	9.215	202.4
C	67.65	12.70	190.7	-	-	-	-	-	-	68.06	12.73	190.1
D	49.18	11.03	224.7	-	-	-	-	-	-	48.60	10.99	226.5
E	40.70	8.409	189.5	-	-	-	-	-	-	40.88	8.395	187.9

During the vehicle inspection period, it was noted that the operational temperature of hydraulic system (about 37.8 °C) tended to increase 5 °C in some equipment (i.e., Crane), but it did not affect the operation of the hydraulic system. It appeared that some biobased fluids have a lower thermal stability than that of the petroleum based fluids. The viscosity of samples collected at third quarter from a Grader (F-6) showed a very significant viscosity change. This data was considered an outlier. It is possible that the equipment operator or mechanics might have accidentally topped off the system with the petroleum based fluid (SAE 15W-40) instead of BHF. However, this contamination problem was not observed anymore during the fourth quarter. It appears that the significant amount of top off fluid may change the viscosity of existing fluid in the system. Overall, no significant viscosity changes were observed in any equipment used in this demonstration.

The oxidation stability is the ability of fluids to resist oxidation at elevated temperatures. This property is another important operational parameter in military hydraulic systems and directly affects fluid service and storage life. Most hydraulic fluids contain some degree of the oxidation inhibitors to reduce the oxidation process during service. In a visual inspection, if a fluid is oxidized, it is usually demonstrated by a darkening in color and the change in viscosity. In addition, the fluid may be decomposed and polymerized in the system. Eventually, this property can lead to degraded service life. Several laboratory tests are available to measure this property. Currently, the ASTM D 664, Acid Number of Petroleum Products by Potentiometric Titration, is widely used to measure the oxidation stability of fluid. In this test, Acid Number (typically referred to as TAN) is the most common measure of fluid acidity and represents its degree of degradation. Generally, increasing TAN over time indicates deterioration of the fluid. Table 9 presents the test results of TAN obtained from the field samples.

The test results showed that the TANs of fluids were very stable over times and marked low values. Some of fluids tended to decrease their TANs over time rather than increase. Based on these data, it is difficult to make a judgment for the oxidation or deterioration of the fluids because there was no other indication of oxidation or deterioration in the field samples.

To verify these results, another oxidation test was conducted using the ASTM D 6186,

Oxidation Induction Time of Lubricating Oils by Pressure Differential Scanning Calorimetry (PDSC). This method is also widely used to measure the oxidation stability of fluids under oxygen environments. In this test, the degree of oxidation stability at a given test temperature is determined by an induction time. One benefit of this test is that it is used to calculate the oxidation of field samples using an oxidation kinetic model⁹.

Table 10 summarizes the PDSC test results obtained at 180 °C. Sample F-2 does not show consistent results at each quarter. In this PDSC test, the induction times of fluids always decrease with time due to the oxidation of fluid. Therefore, it is suspected that the data obtained from F-2, except for the first quarter, may be the resulted accidental top off with the other types of biobased fluids or the existing petroleum based fluids. Generally, all samples showed some degree of oxidation in the equipment and storage. This is considered a part of the fluid aging process. It was reported that the field samples were oxidized range from up to 53.8 % for this testing period. If a fluid was oxidized more than 90 % in this test, its useful life is over and it requires an oil change with new fluid. The data obtained from original drums showed very low oxidation occurred in the fluids.

Table 9. Test Results of Total Acid Number

Sample Code	1Q	2Q	3Q	4Q
F-1	0.40	0.35	0.37	0.41
F-2	0.24	1.1	0.91	0.42
F-3	0.62	0.42	0.45	0.42
F-4	1.29	0.88	0.88	0.40
F-5	1.62	0.79	0.89	0.64
F-6	0.70	0.77	1.95	0.81
F-7	0.36	0.63	0.63	0.23
F-8	0.90	0.69	0.56	0.45
F-9	0.45	0.64	0.58	0.48
F-10	1.02	1.03	1.34	0.88
A	0.21			0.23
B	0.94			1.07
C	1.06			0.83
D	0.33			0.10
E	1.67			1.52

Unit: mg KOH/g

Table 10. PDSC Test Results (minutes) at 180 °C

Sample Code	Vehicle Number	New Fluid	1Q	2Q	3Q	4Q	% Oxidation
F-1	B210	36.06 (A)	24.87	29.25	32.04	18.5	8.4
F-2	B213	2.88 (D)	2.0	9.03	7.55	7.48	9.8**

F-3	B401	4.14 (D*)	3.07	3.49	4.64	3.79	0.5
F-4	B400	39.3 (E)	39.33	40.65	38.54	27.9	2.8
F-5	B156	39.31 (E)	14.66	15.55	21.7	17.3	12.2
F-6	B122	36.06 (A)	19.47	18.26	65.8	17.41	9.9
F-7	B931	39.3 (E)	32.05	41.44	43.68	40.1	0.01
F-8	B840	4.53 (B)	3.87	2.62	2.73	1.02	53.8
F-9	B309	4.53 (B)	2.4	2.62	2.84	2.15	27.1
F-10	B310	19.7 (C)	6.39	5.66	5.98	6.01	23.6
A	Drum	36.06	-	-	-	36.1	6.8
B	Drum	7.8	-	-	-	7.7	7.7
C	Drum	19.7	-	-	-	19.4	0.08
D	Drum	2.88	-	-	-	2.29	5.7
D*	Drum	4.14	-	-	-	4.14	0
E	Drum	39.3	-	-	-	26.74	2.4

* Different Batch of Fluid ** calculated based on 1Q data

All fluids tested remained in good condition and there was no major degradation during this demonstration. Fluid B tested in an Excavator (F-8) had a higher oxidation (53.8 %) than the others. This result agreed somewhat with the viscosity test, but it did not directly agree with the acidity test. It appeared that the additives used in Fluid B may have depleted during this period and fluid became increasingly more acidic. Generally, the increasing in TAN of fluid indicates the depletion of the oxidation inhibitor utilized in fluid. In fact, the reduction of oxidation inhibitor in fluid tends to increase its oxidation rate.

Low temperature properties of BHF's are important, particularly when storing fluids in cold environments or when hydraulic systems are subjected to periods of nonoperation in cold environments. Formation of gels or crystals or separation of components can cause clogging of filters, plugging of small orifices and clearances thus resulting in lack of lubrication to vital components. The freezing of fluid in the reservoir will create pumping problems in the field. The low temperature properties of fluids are directly related to their viscosity grades. A low viscosity grade provides a better low temperature performance in a low temperature environment. The field samples classified in ISO VG 22, 46, and 68 have different low temperature properties in cold environments. Their low temperature properties were measured using the ASTM D 6351, Determination of Low Temperature Fluidity and Appearance of Hydraulic Fluids. Table 11 presents their low temperature characteristics. There was no change of low temperature stability before or after the field demonstration. In addition, none of fluids failed in the field and their low temperature performance was the same as those of the existing petroleum based fluids. It is noted that the lowest temperature during the field testing at Fort Leonard Wood was around 0 °C.

Table 11. Low Temperature Stability Test (°C)

Sample Code	1Q			2Q			3Q			4Q		
	-15	-25	-40	-15	-25	-40	-15	-25	-40	-15	-25	-40
F-1	Flow	Flow	Flow	Flow	Flow	Flow	Flow	Flow	Flow	Flow	Flow	Flow
F-2	Flow	Flow	Frozen	Flow	Flow	Frozen	Flow	Flow	Frozen	Flow	Flow	Frozen
F-3	Flow	Flow	Frozen	Flow	Flow	Frozen	Flow	Flow	Frozen	Flow	Flow	Frozen
F-4	Flow	Flow	Frozen	Flow	Flow	Frozen	Flow	Flow	Frozen	Flow	Flow	Frozen
F-5	Flow	Flow	Frozen	Flow	Flow	Frozen	Flow	Flow	Frozen	Flow	Flow	Frozen
F-6	Flow	Flow	Flow	Flow	Flow	Flow	Flow	Frozen	Frozen	Flow	Flow	Flow
F-7	Flow	Flow	Frozen	Flow	Flow	Frozen	Flow	Flow	Frozen	Flow	Flow	Frozen
F-8	Flow	Flow	Frozen	Flow	Flow	Frozen	Flow	Frozen	Frozen	Flow	Frozen	Frozen
F-9	Flow	Flow	Frozen	Flow	Frozen	Frozen	Flow	Frozen	Frozen	Flow	Flow	Frozen
F-10	Flow	Flow	Frozen	Flow	Flow	Frozen	Flow	Flow	Frozen	Flow	Flow	Frozen
A	Flow	Flow	Flow	-	-	-	-	-	-	Flow	Flow	Flow
B	Flow	Flow	Frozen	-	-	-	-	-	-	Flow	Flow	Frozen
C	Flow	Flow	Frozen	-	-	-	-	-	-	Flow	Flow	Frozen
D	Flow	Flow	Frozen	-	-	-	-	-	-	Flow	Flow	Frozen
E	Flow	Flow	Frozen	-	-	-	-	-	-	Flow	Flow	Frozen
SAE 15W-40	Flow	Gelling	Frozen	-	-	-	-	-	-	-	-	-
MIL-PRF-2104	Flow	Slow flow	Frozen	-	-	-	-	-	-	-	-	-

Hydrolytic stability is the ability of hydraulic fluids to resist reaction with water. Even though the hydraulic system is well sealed, the moisture is difficult to exclude because temperature changes cause reservoir breathing and condensation of moisture from environments. Some of ester based fluids can absorb moisture from the environment. Then, the ester is hydrolyzed to an acid and alcohol. For this reason, the high water content in fluids may affect fluid life, and cause corrosion and biodegradation problems in hydraulic systems. Typically, the BHF's tend to have a low hydrolytic stability in compared to the petroleum based fluids. Because of this, fluid samples were monitored at each quarter for water content. Table 12 presents the test results obtained from the ASTM D 6304, Determination of Water in Petroleum Products, Lubricating Oils, and Additives by Coulometric Karl Fisher Titration. The test results showed that field samples did not generate or absorb water.

Volatility is the rate at which a fluid will vaporize. The hydraulic fluid when exposed to high temperatures at atmospheric pressure can result in significant loss of fluid, and tends to increase in both viscosity and density. In addition, highly volatile fluids are more likely to lead to cavitation and hydraulic pump damage. Generally, BHF's do not have a volatility problem at the operating temperature of hydraulic systems (about 50 °C). To verify this property in the field, the evaporation test (ASTM E 1131) was conducted on the field samples. Table 13 summarizes the TGA test results obtained at 100 °C for an hour. It appeared that BHF's did not have a volatility problem in this demonstration.

Table 12. Total Water Content, %

Sample Code	I.D.	1Q	2Q	3Q	4Q
F-1	A	.028	.027	.095	.079
F-2	D	.027	.263	.129	.083
F-3	D	.042	.097	.142	.117

F-4	E	.76	.137	.268	.108
F-5	E	.64	.158	.252	.184
F-6	A	.106	.345	.592	.271
F-7	E	.065	.146	.141	.103
F-8	B	.069	.155	.127	.077
F-9	B	.074	.217	.298	.201
F-10	C	.094	.137	.205	.183
A	Drum	.042	-	-	.042
B	Drum	.052	-	-	.087
C	Drum	.061	-	-	.077
D	Drum	.050	-	-	.055
E	Drum	.068	-	-	.142
SAE 15W-40	Drum	.315	-	-	-
MIL-PRF-2104	Drum	.267	-	-	-

Table 13. TGA Test Results (%) at 100 °C, 1 hr

Sample Code	Vehicle Number	New Fluid	1Q	2Q	3Q	4Q
F-1	B210	0.813 (A)	1.896	0.989	1.716	1.675
F-2	B213	1.508 (D)	1.812	0.933	0.6963	0.660
F-3	B401	1.508 (D)	1.288	1.898	1.676	1.328
F-4	B400	0.325 (E)	0.457	0.542	0.4623	0.438
F-5	B156	0.325 (E)	1.12	0.972	2.696	1.038
F-6	B122	0.813 (A)	1.21	2.76	0.5750	1.235
F-7	B931	0.325 (E)	0.662	1.196	1.417	0.829
F-8	B840	0.842 (B)	0.981	0.961	0.9822	0.924
F-9	B309	0.842 (B)	1.11	1.136	0.8971	0.910
F-10	B310	0.218 (C)	0.981	0.554	0.4916	0.436
A	Drum	0.813	-	-	-	1.387
B	Drum	0.842	-	-	-	0.798
C	Drum	0.218	-	-	-	0.173
D	Drum	1.508	-	-	-	1.4
E	Drum	0.325	-	-	-	0.358

Seals sometimes fail to perform their designed function of retaining hydraulic fluids and excluding contaminants because of incompatibility between the seal elastomer and the hydraulic fluid. The deterioration of elastomer seals results in the failure of hydraulic power and cause leaking of fluids. Numerous seal materials are currently used in the hydraulic systems. They are basically divided into two groups. One is natural rubber and the other one is a synthetic elastomer. Their formulations and physical properties are not same. Such materials are usually modified by additives, fillers, and other ingredients and then cured to make a finished elastomer compound. The number of basic elastomers

is small, but the variety of finished compounds that can be made is almost infinite. The hydraulic fluid usually has more effect on the seal or packing compound than the compound has on the hydraulic fluid. In most instances the compound is almost inert as far as any harmful effects on the fluids are concerned unless additives in the seal materials are extracted by the fluid. However, some fluids can attack and destroy seal materials.

The best method of determining whether a fluid and an elastomer are compatible is to observe the use in actual hydraulic systems. Unfortunately, this approach is almost impossible in the practical sense due to the variation of seal materials being used in the equipment. For this reason, most of hydraulic fluid specifications often require a reference elastomer for the elastomer compatibility test.

The biobased hydraulic fluid specification also uses SAE reference elastomer (AMS 3217/2B) with its specification limit for the seal compatibility test. This reference elastomer was specially formulated with Nitrile or Buna N (NBR-L) material and is widely used in the many hydraulic specifications including military specifications. The swelling limits (10 to 30 percent) used in this specification were developed based on the previous field demonstration for biobased hydraulic fluids.

Prior to the field demonstration, all samples were evaluated according to the laboratory elastomer compatibility test method and had passed its specification requirement. During the field demonstration, none of the equipment had seal material failures nor had a leaking problem in any part of their components.

Metal compatibility is a very important property in a hydraulic fluid. The copper, silver, bronze, aluminum, steel, iron and many other metals are commonly used as structural materials in hydraulic systems. Normally, the corrosion or rust on metal surface is one of indications for the incompatibility of fluids. The fluid compatibility with metals can be measured by a number of tests. These techniques usually involve exposing the metal to the fluid under a variety of conditions and determining any changes in the fluid or the metals. The biobased hydraulic fluid specification requires three different types of corrosion tests to evaluate the compatibility between fluids and metals: copper corrosion test, galvanic corrosion test, and rust prevention test in synthetic seawater. These corrosion tests were originally designed to evaluate specific corrosion characteristics of fluids in different applications and environments. One example is the galvanic corrosion test that is designed to determine the fluid-metal compatibility between dissimilar metals during use. Like the conventional petroleum based hydraulic fluids, the biobased fluids must be compatible with all common metals used in construction of hydraulic systems. To verify this property in the field, all field samples including existing petroleum based fluids were analyzed using an X-ray technique.

Table 14 (a-b) summarizes the results of element analysis for all samples. In this element analysis, 12 chemical materials including five metals (Fe, Ni, Mg, Cu, and Zn) were analyzed. Unlike the petroleum based fluids, the BHF's evaluated did not contain organo-metal additives. However, field samples contaminated with petroleum based fluid showed Zinc metal in this analysis. This metal was also found in the engine oils and it appeared that this element came from the ZDDP anti-wear additive utilized in the MIL-PRF-2104 petroleum based fluids. The BHF's did not show any evidence of incompatibility between BHF's and structural materials in hydraulic systems.

Table 14(a). Elemental Analysis by X-ray Method

Sample ID	Concentration – ppm											
	Mg	Si	P	S	Cl	Ca	Cr	Mn	Fe	Ni	Cu	Zn
A	0	0	380	667	0	0	0	0	0	0	1	0
B	0	0	0	0	45	711	0	0	0	0	0	0
C	0	0	193	856	0	13	4	0	0	0	0	0
D	0	0	528	1166	0	14	0	0	0	0	0	0
E	0	0	189	823	0	13	0	0	1	0	2	0
SAE 15W-40	274	0	1303	4469	126	2174	0	0	3	0	0	1338
MIL-PRF-2104	0	27	1098	7000	157	2547	0	0	2	1	0	1140
F1-0	396	40	1042	7793	281	1475	0	0	27	0	62	1079
F2-0	451	17	1050	8022	268	1492	0	0	18	0	25	1101
F3-0	268	30	1050	4638	127	1814	0	0	3	0	1	1074
F4-0	260	10	1058	6288	144	2030	0	0	6	0	1	1127
F5-0	487	24	949	6398	396	1233	0	0	13	1	43	977
F6-0	452	0	961	5537	183	1191	0	0	15	1	284	1004
F7-0	314	24	780	4901	264	1373	0	0	20	1	5	814
F8-0	564	0	1010	6958	321	1483	0	0	11	1	71	1123
F9-0	694	0	1010	4456	136	1059	0	0	0	0	102	1057
F10-0	696	27	1018	4465	120	979	0	4	4	0	110	1065
F1-1	0	0	448	1425	0	198	0	0	2	0	5	118
F2-1	151	40	566	1870	0	268	0	0	3	0	0	121
F3-1	93	0	670	2124	0	476	0	0	0	0	0	273
F4-1	85	0	454	2328	0	551	0	0	0	0	1	306
F5-1	284	0	477	3171	172	521	0	0	2	1	21	418
F6-1	247	0	596	2692	89	491	0	3	6	1	12	405
F7-1	88	7	353	2022	77	405	0	0	5	0	0	236
F8-1	310	13	400	3180	128	545	0	0	3	1	46	409
F9-1	105	0	225	1475	0	164	0	0	0	0	19	163
F10-1	181	0	387	1785	0	257	0	0	0	1	38	266
F1-2	0	0	440	1429	0	196	0	0	1	0	6	120

Table 14(b). Elemental Analysis by X-ray Method

Sample ID	Concentration – ppm											
	Mg	Si	P	S	Cl	Ca	Cr	Mn	Fe	Ni	Cu	Zn
F2-2	0	0	313	1141	0	66	0	0	0	1	0	39
F3-2	96	0	650	2120	0	493	0	3	3	1	0	294
F4-2	0	13	358	1997	0	445	0	0	0	0	2	243
F5-2	244	0	462	2493	108	395	0	0	0	0	17	312
F6-2	236	0	586	2497	46	460	0	0	8	0	109	377

F7-2	49	0	383	1615	0	277	0	0	2	0	0	168
F8-2	335	0	403	2595	116	527	0	0	1	0	50	404
F9-2	131	0	240	1666	0	216	0	0	0	1	23	217
F10-2	140	0	358	1590	0	214	0	0	0	0	31	215
F1-3	36	37	433	1416	0	197	0	0	5	1	6	125
F2-3	0	0	329	1200	0	707	0	0	0	1	2	509
F3-3	44	0	656	2222	0	509	0	0	1	0	0	312
F4-3	0	34	380	2065	0	475	0	0	2	0	0	264
F5-3	178	34	532	2650	132	556	0	0	4	0	18	432
F6-3	270	30	1166	4723	141	1979	0	0	7	0	42	1224
F7-3	38	0	360	1603	0	272	0	0	4	1	0	166
F8-3	33	2	240	1921	0	290	0	0	0	0	27	220
F9-3	137	0	281	1781	0	247	0	0	0	0	27	252
F10-3	147	0	358	1628	0	217	0	0	0	0	36	225
F1-4	0	0	471	1535	0	243	0	0	0	0	6	147
F2-4	0	0	324	1200	0	74	0	0	0	0	2	54
F3-4	81	0	685	2247	0	545	4	0	0	0	0	325
F4-4	30	0	369	1883	0	407	0	0	2	1	4	239
F5-4	210	0	559	2705	140	565	0	0	3	0	24	447
F6-4	214	13	590	2514	102	454	0	0	4	1	122	388
F7-4	0	0	364	1586	72	269	0	0	5	0	0	171
F8-4	36	0	241	1904	0	294	0	0	3	0	58	232
F9-4	154	0	298	1895	0	284	0	0	0	0	40	276
F10-4	156	13	365	1683	0	228	0	0	0	1	48	238
A (4Q)	0	0	366	657	0	0	0	0	0	0	0	0
B (4Q)	0	0	51	924	0	5	0	0	0	0	0	0
C (4Q)	0	0	196	839	0	13	0	0	0	0	2	0
D (4Q)	0	0	530	1179	0	13	0	0	0	1	1	0
E (4Q)	0	0	125	766	0	0	0	0	0	0	1	0

Environmental compatibility of hydraulic fluids is a very important parameter today. A common problem in most hydraulic systems is the potential for leakage and the possibility of hydraulic fluid spilling during use. The generation of hazardous wastes from fluids results in both short- and long-term liability in terms of cost, environmental damage, and mission performance. To resolve this problem, the biobased hydraulic fluids are currently used in environmentally sensitive areas such as construction, forestry, mining, and river. The major benefits of biobased fluids are low toxicity and high biodegradability. In addition, they are non-carcinogenic, and do not contain any prohibited ingredients listed by EPCRA, CERCLA, and RCRA.

During the field demonstration, the BHF's were handled by a normal maintenance procedure and did not give any skin and eye irritation on maintenance people. One of questions raised in this study

was whether the field samples still can provide a high biodegradability when compared with their original fluids. Any incompatibility between fluids may reduce their biodegradability due to the chemical reaction. Generally, the biodegradability of the fluid depends on its material and chemical structure. It was observed that the BHFS did not biodegrade in the hydraulic systems (i.e., reservoirs) during the field demonstration.

To determine the biodegradability of fluids, the field samples were analyzed to predict their biodegradability according to the ASTM D 7373, Predicting Biodegradability of Lubricants using a Bio-kinetic Model. Table 6 summarizes the composition analysis for field samples and their predicted biodegradability is presented in Table 15. To verify these results, the actual biodegradation tests were also conducted using fourth quarter samples according to the ASTM D 6731, Determining the Aerobic, Aquatic Biodegradability of Lubricants or Lubricant Components in a Closed Respirometer. These test results are also presented in Table 15. The test results showed that all field samples did not change their biodegradability in the systems and storages (drums) over time. The field samples containing petroleum fluid had a relatively lower biodegradability than BHF's because the petroleum based fluids generally are considered non-biodegradable products. There was no indication of chemical degradation in this composition analysis.

In the changeover or adding hydraulic fluids, one question was the compatibility of biobased fluid versus the existing petroleum based fluid in the construction equipment. Incompatibility of fluids is usually evident in their physical and chemical properties. Typically, it shows in the viscosity tests and evaporation loss, composition analysis, or seal compatibility test due to their internal chemical reaction. As mentioned earlier, all samples were already contaminated with the existing petroleum based fluids (18 to 40.1 %). During the field demonstration, no sign of incompatibility between two fluids was observed and all laboratory data supported this result. It implied that the biobased fluid can easily be changed over from the existing petroleum based fluid without any major cleaning effort to the system.

Table 15. Biodegradability of Field Samples

Sample Code	Tested Sample Composition	ASTM D 7373		ASTM D 6731
		1Q (%)	4Q (%)	4Q (%)
F-1	A (80.3%) + P [*] (19.7%)	64	68	60.8
F-2	D (83.2%) + P (16.8 %)	66	68.8	74.8
F-3	D (66 %) + P (34 %)	59	60	67.3
F-4	E (82 %) + P (18 %)	55.4	59.8	57
F-5	E (69.3 %) + P (30.7 %)	49.4	48	ND
F-6	A (59.1 %) + P (40.9 %)	41	42	61.7 [*]
F-7	E (76.4 %) + P (23.6 %)	52.4	53.4	69
F-8	B (57.9 %) + P (42.1 %)	55.7	63.4	64.4
F-9	B (81.9 %) + P (18.1 %)	66.7	67.9	71.3
F-10	C (71.2 %) + P (28.8 %)	59.2	58.6	74.1 [*]
A from Drum	100% Bio-based Fluid	66	66	66
B from Drum	100% Bio-based Fluid	76.7	74	72.7
C from Drum	100% Bio-based Fluid	67	69.7	68.3
D from Drum	100% Bio-based Fluid	75.6	75	85
E from Drum	100% Bio-based Fluid	68	68.5	71
SAE 15W-40 from Drum	100% Petroleum Fluid	33.7	-	34.1
MIL-PRF-2104 from Drum	100% Petroleum Fluid	22.6	-	30.0

- Petroleum based existing fluid (SAE 15W-40 or MIL-PRF-2104).

* Considered as an outlier due to the test equipment problems.

IV. CONCLUSIONS

Field demonstration to evaluate the performance of biobased hydraulic fluids in pieces of construction equipment was successfully completed. The tested biobased fluids did not show any abnormal behavior in this demonstration and provided performance equivalent to the existing petroleum based fluids. In addition, no equipment failed or was damaged due to the biobased fluids. During this period, neither biodegradation nor chemical degradation was observed in hydraulic fluid systems and reservoirs. One concern in this demonstration was the low temperature stability and operability of biobased fluids in the field environment. The tested fluids, except for Fluid A, were not formulated for use at extreme low temperatures (i.e., -40 to -54 °C). In this demonstration, it was observed that fluids did not have low temperature operational problem due to the milder Midwest winter weather.

The physical and chemical properties of fluids were slightly changed due to the aging of the fluids. This is considered a normal degradation process of any fluid. Typically, the biodegradability of the

tested fluids did not change during the field demonstration. In addition, the biobased fluids did not show any incompatibility with the existing petroleum based fluids and the seal materials used in construction equipment. It appears that the biobased fluid can easily be changed over from the existing fluids without any major cleaning effort to the hydraulic system. A small amount of petroleum based hydraulic fluid does not create any incompatibility or operational problems in the system. In addition, the field demonstration results were found to be in good agreement with the laboratory performance test used in this study.

All field demonstrations were successfully completed, met original milestones, and did not impact the military mission of the unit in any way. The overall performance of BHF's have been proved in the field demonstration and accepted by military users. Therefore, the BHF's can be used as an operational fluid for military construction equipment.

RECOMENDATIONS

- Select biobased fluids meeting MIL-PRF-32073 as military operational fluids for construction equipment.
- Conduct extended field demonstration to determine extend of service life for biobased fluids in construction equipment.
- Consider a study to convert waste biobased fluid to a biofuel.

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APPENDICES

A. Photos taken from Field Demonstrations

B. QPL Data for Tested Biobased Hydraulic Fluids

APPENDIX A. PHOTOS TAKEN FROM FIELD DEMONSTRATION AT FORT LEONARD WOOD



A.1 Draining the existing fluid for field demonstration preparation



A.2 Excavator



A.3 Scraper



A.4 Loader



A.5 Crane



A.6 Bulldozer



A.7 Grader



A.8 Fluid sample collection at each quarter



A.9 Equipment Inspection



A.10 Biobased Hydraulic Fluids



A.11 Sample collection from Loader



A.12 Crane Operation with Biobased Hydraulic Fluid



A.13 Equipment Demonstration with Biobased Hydraulic Fluid

APPENDIX B. QPL DATA FOR TESTED BIOBASED HYDRAULIC FLUIDS

Test	Method	BHF-01	BHF-02	BHF-07	BHF-08	BHF-09
Specification Grade		2	4	5	4	3
ISO Grade		22	46	68	46	-
Viscosity, 40 deg C min, cSt	ASTM D445	22.62	41.99	68.57	46.63	40.29
Viscosity, 100 deg C min, cSt	ASTM D445	4.955	9.2	12.8	10.42	8.372
Viscosity Index, min	ASTM D2270	150.9	209.9	189.9	221.2	190.5
Viscosity, -15 deg C, max cSt	ASTM D445	172.04	881.17	1696.3	811.21	836.92
Pour Point, deg C, max	ASTM 97	-51	-44.3	-37	-32	-35
Flash Point, deg C, min	ASTM D92	194	298	291	273	264
Acid or Base Number, mg KOH/g, max	ASTM D664	0.197	0.63	1.157	0.343	0.615
Water Content, %, max	ASTM D 6304	0.006	0.037	0.027	0.0215	0.007
Rust Prevention	ASTM D 665B	Pass	Pass	Pass	Pass	pass
Copper Corrosion, max	ASTM D 130	1a	1a	1a	1b	1a
Galvanic Corrosion	FTM 5322	Pass	Pass	Pass	Pass	Pass
Low Temperature Stability, 72 hrs	FTM 3458	Pass @-40C	Pass @-15C	Pass @-15C	Pass @-15C	Pass @-25C
Oxidation Stability (PDSC) minutes, min	ASTM D 6186	17.9 @180C	33.03 @155C	104 @155C	35.85 @155C	38.0 @180C
Swelling of Synthetic Rubber, NBR, L, %	FTM 3603	30.5	20.63	11.17	12.76	20.05
Evaporation Loss, %, 100 deg C, 1 hr, max	ASTM E1131	0.8	0.826	0.182	0.924	0.193
Four Ball Wear, mm, max	ASTM D 4172	0.405	0.381	0.39	0.419	0.364
Biodegradability, %, min	ASTM D5864	66	72.7	68.3	85	71
Foaming	ASTM D892	Pass	Pass	Pass	Pass	Pass
Workmanship	Army Method	Pass	Pass	Pass	Pass	Pass
Particle Size (ISO)	Particle Count	16,14,9	21,19,12	21,18,13	19,16,11	21,18,12
Trace Sediment, %	ASTM D 2273	0.005	0.00	0.00	0.00	0.00